Systems Engineering for Space Exploration Medical Capabilities

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Human exploration missions that reach destinations beyond low Earth orbit, such as Mars, will present significant new challenges to crew health management. For the medical system, lack of consumable resupply, evacuation opportunities, and real-time ground support are key drivers toward greater autonomy. Recognition of the limited mission and vehicle resources available to carry out exploration missions motivates the Exploration Medical Capability (ExMC) Element's approach to enabling the necessary autonomy. The Element's work must integrate with the overall exploration mission and vehicle design efforts to successfully provide exploration medical capabilities. ExMC is applying systems engineering principles and practices to accomplish its goals. This paper discusses the structured and integrative approach that is guiding the medical system technical development. Assumptions for the required levels of care on exploration missions, medical system goals, and a Concept of Operations are early products that capture and clarify stakeholder expectations. Model-Based Systems Engineering techniques are then applied to define medical system behavior and architecture. Interfaces to other flight and ground systems, and within the medical system are identified and defined. Initial requirements and traceability are established, which sets the stage for identification of future technology development needs. An early approach for verification and validation, taking advantage of terrestrial and near-Earth exploration system analogs, is also defined to further guide system planning and development.

Nomenclature

ConOps	=	Concept of Operations
ExMC	=	Exploration Medical Capabilities
MBSE	=	Model-Based Systems Engineering
NASA	=	National Aeronautics and Space Administration
SysML	=	Systems Modeling Language

I. Introduction

EXPLORATION missions beyond low earth orbit bring opportunities for enhancing humanity's capabilities. The missions also bring challenges in the development of those capabilities. A driving case of a human mission to Mars will be longer than human space missions to date, and also will lack the medical evacuation, real-time

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communication, and resupply more readily available for current low-Earth orbit operations. In addition, predicting the exact medical conditions for which to plan will not be possible. Therefore, an exploration medical system must provide flexible capabilities to support the care of crewmembers with conditions that were not considered specifically in advance. Medical technologies to be considered in exploration designs will continue to rapidly evolve for the foreseeable future, so the design framework must allow for new technologies. Limited flight resources such as mass, power, volume, and data, are constraints requiring the medical system to be viewed as an integrated part of flight system development for exploration. A systems engineering approach is required to meet the exploration crew health management needs within opposing constraints. The Exploration Medical Capability (ExMC) element of NASA's Human Research Program is undertaking these systems engineering activities [1, 2].

II.   Systems Engineering Approach for the Medical System

A. Systems Engineering Management Approach

There are many ways to approach the practice of systems engineering principles. As the ExMC Systems Engineering (SE) team was established, a Systems Engineering Management Plan, tailored from the NASA Systems Engineering Handbook [3], was developed to capture context, approach and execution information.

The mission of the ExMC SE team is to "Define, develop, validate, and manage the technical system design needed to implement exploration medical capabilities for Mars and test the design in a progression of proving grounds." During the SE team's formulation in 2016, a customized version of a Needs, Approach, Benefits, Challenges (NABC) assessment [4] was developed to communicate the vision for the SE team and its stakeholders. One noteworthy customization was for the "C" portion of the exercise, in which the team addressed "culture" as a specific challenge.

ExMC SE activities will meet the following NEED: Develop the system technical foundation. Specifically, the team will:
- Develop Concept of Operations material
- Capture stakeholder expectations
- Define and manage requirements
- Capture and share system designs
- Identify and manage cross-disciplinary interfaces
- Plan and execute system V&V
- Inform system development decisions from scientific and technical perspectives
- Identify technology development and research needs

The ExMC SE team will take this APPROACH: Apply structured and integrative science and engineering. Specifically, the team will:
- Use a structured and disciplined technical approach to develop a medical system addressing medical, behavioral health, human factors, physiological performance, and task performance needs to ensure crew health and performance
- Enable effective coordination and integration with exploration mission engineering, operational, and technology development efforts

The ExMC SE team will provide the BENEFIT: Increase relevancy to exploration system maturation. Specifically, the team will:
- Communicate in the same language as engineering and operations communities with respect to system design
- Provide regular and transparent communication to maintain programmatic and stakeholder situational awareness and provide insight into the medical system development
- Develop and foster shared mental models within and external to crew health and performance community

The ExMC SE team will operate with the following CULTURE: Be open, unbiased, learning, and serving. Specifically, the team will:
- Develop relationships across disciplines and Centers to build trust and enable teamwork
- Enhance visibility and opportunities for influence on concurrent activities of related groups that otherwise would not happen
- Foster learning of SE principles and practices
- Be both responsive to and anticipatory of stakeholder needs, keeping in mind stakeholders may be from anywhere in an organizational chart

As NASA's exploration plans develop, the ExMC SE work will allow early integration of medical considerations into the designs of missions throughout exploration phases shown in Figure 1, from reference [5].

The team is using the Deep Space Transport Mars verification mission, shown in Phase 2 and currently described as a round-trip human Mars mission without a surface landing, as its current focus of activities.
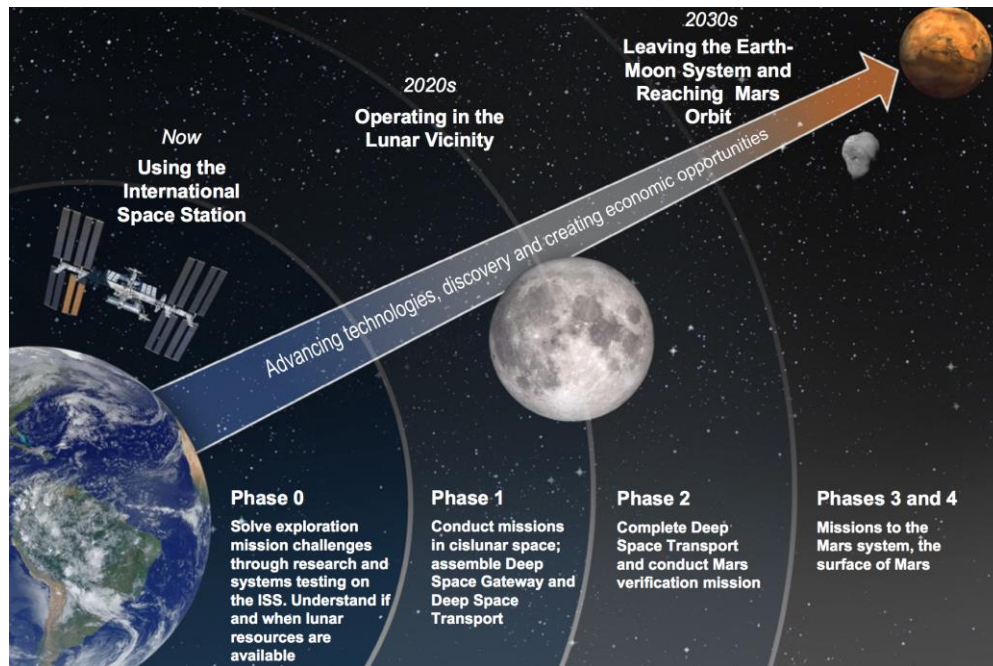

Figure 1. Current NASA plans for exploration.

B. Application of Model-Based Systems Engineering

ExMC is utilizing Model-Based Systems Engineering (MBSE) to support medical system definition and analyses that will inform research activity needs and prioritization. MBSE is an engineering approach used to model the life cycle activities of a project, and provides an alternative to the more traditional document-based approach to engineering. Using a traditional document-based approach to systems engineering can result in cost increases, raise technical risk and create information silos among teams. Diverging from the document-based approach will offer significant savings through avoidance of maintaining disparate documentation that runs the risk of becoming obsolete or inconsistent with evolving project goals. The ExMC system engineering team's use of MBSE, applying the System Modeling Language (SysML) and supporting MBSE tools, is enabling technical communication through the use of shared mental models of the medical system, consistent notation and integrated data sets. These system models will be integral for successful integration of the medical system with exploration vehicles and system verification and validation using terrestrial analogs and precursor exploration missions.

The use of MBSE tools helps to streamline communication, content, and system design across the ExMC SE team that works in different geographic locations and addresses a variety of technical discplines. The SE team's tools are being designed and selected to support meta-data exchange as integration points to crew health, crew performance, and other vehicle system and subsystem models are identified. MBSE is improving shared understanding of system needs and schedules between stakeholders, provides a common language for analysis, and will help to facilitate identification of risks. SysML is being utilized here to provide a controlled common model of the medical system and requirements definition activities. SysML provides diagrams as views into the underlying model, and a subset of examples related to the medical system will be described in this paper.

C. Initial Process Overview

The scope of developing an exploration medical system is a large one. At this early stage, the ExMC Systems Engineering team activities must focus on establishing highly valuable technical products and an infrastructure to support the continued development of additional products later in the medical system life cycle. Figure 2 shows the initial process the systems engineering team is following based on systems engineering activities typical in early design phases [6, 3].
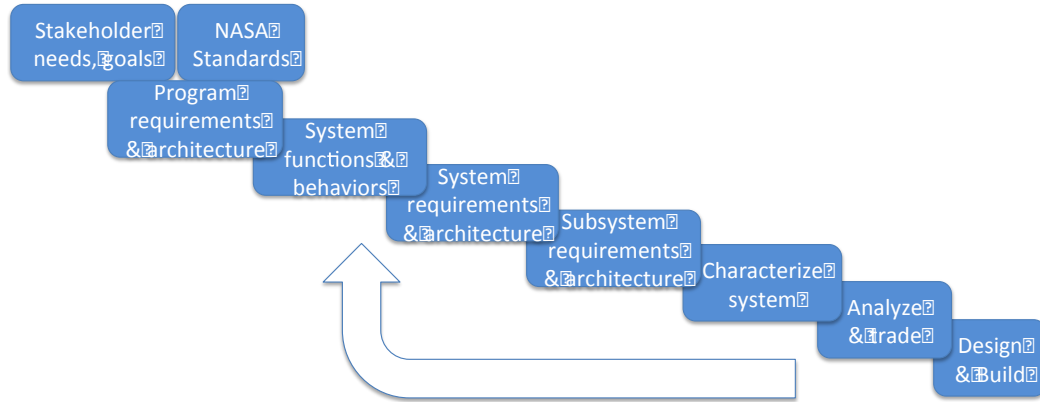
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Figure 2. Initial activities for exploration medical system development.

The team began its efforts with existing information provided in NASA Standards specifically focused on crew health and performance. Additionally, the team defined its set of stakeholders and developed goals for the exploration medical system. In the absence of an exploration program, assumptions were made and documented, and are now being updated based on NASA's current exploration plans [5]. The team captured system goals, assumptions, and operational scenarios in a Concept of Operations (ConOps). The ConOps scenarios were next modeled and extended in SysML to support a functional decomposition analysis. This body of work allows the team to progress to writing medical system functional requirements. As the behavioral content matured, system architecture development began, and will continue to evolve with the generation of requirements.

Once system requirements and an architecture is in place, subsystem architectures will be developed, and requirement allocations will be made. Characterizations of the system options will be performed, including evaluations of important design properties such as mass, power, volume, data needs, medical equipment layout, and risk estimations. The SE team is setting up its set of tools to inform trade study analyses, and identify areas of low maturity that would benefit from design, build, and evaluation activities as part of early exploration missions or ground-based analogs.

III. Medical System Stakeholder Expectations

A. NASA Standards Interpretation: Level of Care Assumptions

NASA medical care standards establish requirements for providing health and medical programs for crewmembers during all phases of a mission. These requirements are intended to prevent or mitigate negative health consequences of long-duration spaceflight, thereby optimizing crew health and performance over the course of the mission. Current standards are documented in the two volumes of the NASA-STD-3001 Space Flight Human-System Standard document, established by the Office of the Chief Health and Medical Officer. Their purpose is to provide uniform technical standards for the design, selection, and application of medical hardware, software, processes, procedures, practices, and methods for human-rated systems. NASA-STD-3001 Vol. 1 [7] identifies five levels of care for human spaceflight, listed in Table 1. Each level has several components listed that illustrate the type of medical care expected. Interpretation of these components and the associated amount and type of care required at each level is dependent upon several factors, including the duration of the mission, accepted amount of medical risk, the level of training of the healthcare provider, terrestrial medical standards, technology and resources available for use in the flight environment, and the time it would take to to get an ill or injured crewmember to a definitive care location.

Level of Care	Capability
I	Space Motion Sickness, Basic Life Support, First Aid, Private Audio, Anaphylaxis Response
II	Level I + Clinical Diagnostics, Ambulatory Care, Private Video, Private Telemedicine
III	Level II + Limited Advanced Life Support, Trauma Care, Limited Dental Care
IV	Level III + Medical Imaging, Sustainable Advanced Life Support, Limited Surgical, Dental Care
V	Level IV + Autonomous Advanced Life Support and Ambulatory Care, Basic Surgical Care

Table 1. Levels of Care (Reference [7], V2, Rev A, Table 13).

4

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ExMC has expanded the context of the levels of care and components to assist the multidisciplinary ExMC team with consistent interpretation as they approach future work [8]. This supplemental information includes definitions for each component of care and example actions that describe the type of capabilities that coincide with the definition. This interpretation is necessary in order to fully and systematically define the capabilities required for each level of care in order to define the medical requirements and plan for infrastructure needed for medical systems of future exploration missions, such as one to Mars. Table 2 gives an example of a definition and capabilities associated with Limited Advanced Life Support, a component listed in Level of Care 3.

Capability	Definition	Example Actions "*" indicates augmentation of action from lower level of care
Limited Advanced Life Support (ALS)	Diagnosis and initial treatment for an emergent medical event. Resources to support medical decision making using data obtained from telemedicine, limited physical exam, vital signs, and clinical diagnostics.	- Control over body positioning and workspace **Airway:** - Reposition airway, insert airway adjuncts *and supraglottic airways - Clear obstructed airway with manual maneuvers - *Suction airway **Breathing:** - Provide breaths using *manual means - *Provide and titrate oxygen via noninvasive/invasive means **Circulation:** - Control bleeding using direct pressure - Provide chest compressions - *Defibrillate using automated device - Measure, record, and trend vital signs (heart rate & rhythm, respiratory rate, blood pressure, temperature, oxygen saturation)

Table 2. Example of an expanded component definition within a Level of Care definition

Clearly defined levels of care, and what capabilities are included in each, provides a common starting point for discussing the medical system; not just for use within the ExMC team but also for communicating with the project's many stakeholders.

B. Stakeholder Needs and System Goals

A thorough understanding of stakeholders' needs and expectations is vitally important and serves as the foundation for other systems engineering activities and products. This process provides ExMC systems engineers with a way to ensure key stakeholders are in agreement and that the realized system will meet expectations. Reaching consensus early in the project on things such as high level capabilities, system characteristics, behaviors and performance is important because it shapes customer expectations, bounds the problem/solution space and establishes criteria to determine if the right system is built and delivered.

ExMC has identified a core set of driving stakeholders that are important in understanding how the system will be used in its operational environment. Driving stakeholders include the Office of the Chief Health and Medical Officer (OCHMO) Health and Medical Technical Authority (HMTA), the Human Research Program (HRP), the Astronaut Office, the Medical Operations community, the Human System Risk Board (HSRB) and international partner representation in coordination with the Crew Health and Preformance (CH&P) System Maturation Team (SMT), under the Human Exploration and Operations Mission Directorate (HEOMD). Refer to Figure 3 to see relationships between the driving stakeholders and ExMC. Red numbered text indicates primary types of outputs from ExMC.
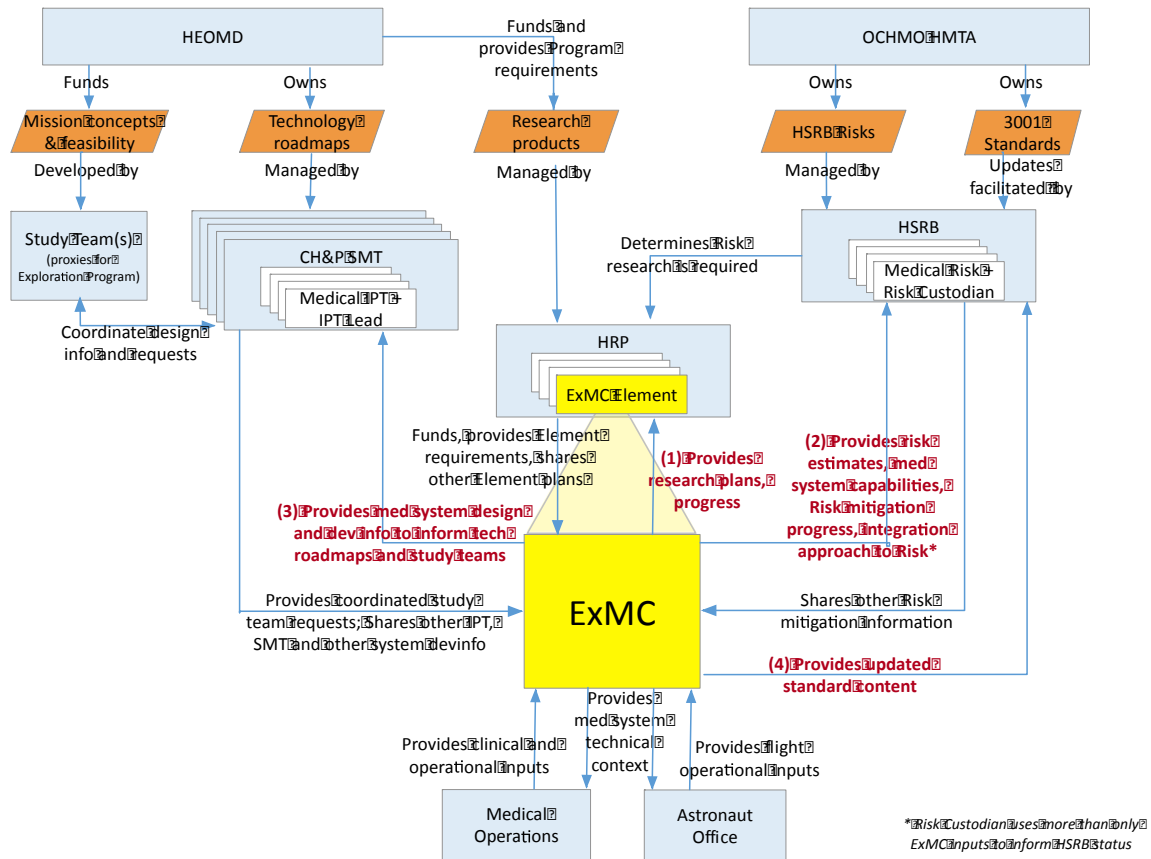
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Figure 3. ExMC interactions with driving stakeholders.

A set of system goals has been developed to provide a foundation for exploration medical system development. They are based on stakeholder expectations and constraints levied or imposed on the medical system. These goals influence technical measures commonly used for insight into performance of the technical solution, and establish the basis for high-level requirements and quality attributes of the medical system.

Comprehensive Health Management
Provide comprehensive health management capabilities to enable mission task performance and mission success.
Recognizing the extended duration and distance from Earth during exploration missions, in-mission care capabilities must span prevention, diagnosis, treatment, and long term management for both clinical and well-being aspects of health. These capabilities will use resources (e.g., skillsets, software, hardware, medication) to prepare for and execute planned and unplanned medical operations, pharmacy operations, personalized medicine, training, resource management, ethics considerations, data management, and risk estimation.

Crew Autonomy
Enable crew autonomy in medical task execution and decision-making.
Although ground medical support will remain an important part of medical care, the autonomous care model for exploration requires flight surgeons and other support staff to fill a consultant role. The mission physician astronaut will serve as director of care during real-time medical events and will be the primary source for in-mission medical decision-making. To support the physician astronaut this medical care paradigm requires comprehensive vehicle capabilities and resources in the form of onboard medical references, smart diagnostics, and decision support systems.

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Continual Information Application and Learning
Support medical system knowledge augmentation over the mission lifetime.
It is desired to be able to use knowledge gained both in-mission and on the ground to update medical system elements, such as task training, decision support, and models for estimation and prediction of crew health and system status.

System Flexibility and Extensibility
Balance conflicting needs for medical system resource conservation (in design and in mission) and medical system operations.
Flexibility and extensibility are needed because the in-mission resources will be constrained and because of the inability to definitively predict all medical conditions that will occur during the mission. Medical flexibility helps identify the broadest use opportunities for a limited resource set relevant for clinical needs. Extensibility addresses conditions and situations outside of the target design conditions.

Medical, Vehicle, and Mission Systems Integration
Integrate hardware, software, human, and operational aspects of the medical system with the mission and vehicle design.
The in-mission medical system should be viewed as a component of the overall integrated vehicle system. When allowed and appropriate, medical data and information should be shared with other vehicle system components, and vice versa.

Crew and the Medical System Integration
Design the medical system to fit the needs, abilities, and limitations of the crew.
A well-designed medical system minimizes training time and operations complexity and lowers mission medical risk. It accounts for the various modes of data entry, input devices, computing platforms, and user preferences employed on the vehicle and incorporates human system integration and human factors guidelines to reduce the cognitive and physical workload while using the medical system. A well-designed, usable medical system is easy to learn and operate, keeps the user informed on what is going on, reduces the number of errors and makes them easy to recover from, and assists in the timely completion of tasks. The expectation is that unobtrusive automated and manual processes are available to support crew activities.

Ground Awareness
Maintain ground situation awareness of crew health and medical system status as flight communication constraints permit.
The ground support system will continue to be informed on the state of the crew and medical system to assess impacts to the mission goals and objectives and to provide support as needed.

Defining the medical system goals enabled fruitful discussions with stakeholders at an early stage, and provided initial insight into the functions the medical system will need to provide.

C. Concept of Operations
The Medical System Concept of Operations for Mars Exploration Missions outlines the capabilities required to ensure appropriate medical care for the crew of a highly autonomous future NASA mission to Mars. This Concept of Operations (ConOps) document decomposes the overall mission into a series of mission phases, starting with Earth-based launch and concluding with Earth entry, descent, and landing. When complete, the ConOps will illustrate the potential medical capabilities for each mission phase through sets of medical scenarios, involving the crew, onboard equipment and tools, and ground personnel. Each scenario consists of a context description (e.g. dental exam), a highlighted functionality list, assumptions, an activity flow chart (see Figure 4), and a narrative text to provide context for the flowchart. Collectively, these scenarios enable ExMC to use MBSE tools for planning, designing, and prototyping an integrating a medical system for preventing, diagnosing, treating, and managing long-term the health and medical risks inherent to human exploration missions to Mars.

Initial development of the ConOps is focusing on the Mars transit (cruise to Mars) phase, which has been organized initially into twelve scenarios, each defined by the nature of the activity, who is involved with the activity, and whether the acivity is planned or unplanned. For example, the following activity flowchart represents a planned (routine) dental exam involving a patient, a caregiver, the medical system, the ground system, and the vehicle system:
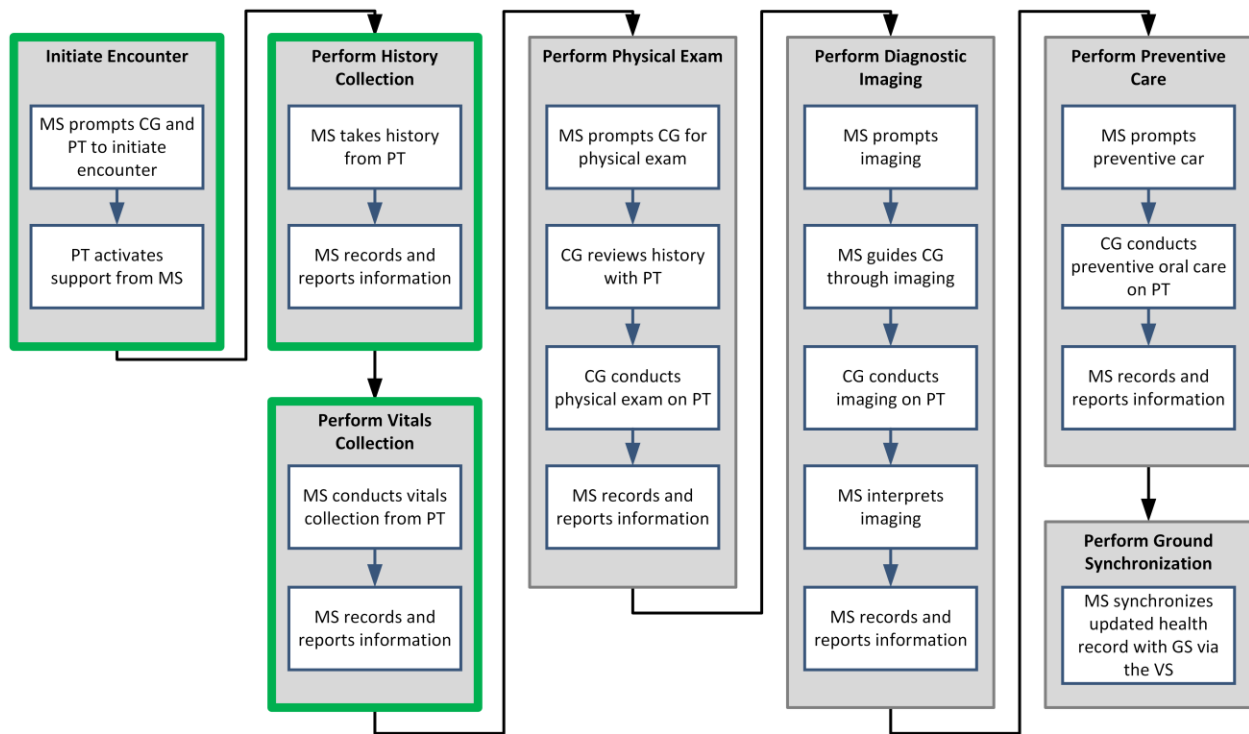
Figure 4. Flow chart of activities in the dental exam scenario.

The narrative text associated with the highlighted boxes is provided below as an example:

The medical system sends an alert to the physician astronaut and patient that a scheduled dental exam will start in ten minutes. The patient heads over to the medical bay and picks up a display, which uses biometric analysis to identify him and grants him access to his health record in the medical system.

The medical system starts the appointment by prompting him to review his health record documentation for accuracy and update if needed. Areas of review include: past medical, surgical, and dental treatment history, allergies, current medications, and then a series of questions to complete a review of systems. It then uses biosensors to collect vital signs from the patient, such as blood pressure, heart rate, oxygen saturation, temperature, and respiratory rate. These are all automatically saved to his health record and displayed back to him.

Each scenario is intended to demonstrate a set of functions. For the dental exam scenario, those funtions are:
   a) prompt the initiation of an activity per the crewmember's schedule
   b) prompt the initiation of an activity based on a protocol
   c) retrieve information from the patient
   d) guide a crewmember during an activity
   e) interpret information gathered during an activity
   f) provide varying levels of support to a crewmember

While the Mars Transit phases content currently comprises 12 scenarios, additional scenarios may be added as needed, and other phases scenarios will vary in quantity, subject, and functionality.

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IV. Medical System Behavior Descriptions

A. Medical System, Crew, and Flight System Activities

Flow charts from the ConOps are analyzed and translated into Activity Diagrams in a SysML model. An example Activity Diagram of the first portion of the Dental Exam scenario is shown in Figure 5. This clarifies the activities expected to be performed by the medical system, each crewmember (whether in a patient or caregiver role), and the other flight or ground systems. Each horizontal swimlane represents actions performed by either the Patient, Caregiver, or Medical System. For example, one action "Prompts CG and PT to initiate encounter," under the "Initiate Encounter" box defined in the ConOps flow chart (Figure 4) can now be understood to be performed by the Medical System, and the other action "Activates support from MS", will be performed by the Patient. The "Prompts CG and PT to initiate encounter" and "Conducts vitals collection on PT" actions represented in the Medical System swimlane will be discussed in other SysML diagrams throughout this paper.
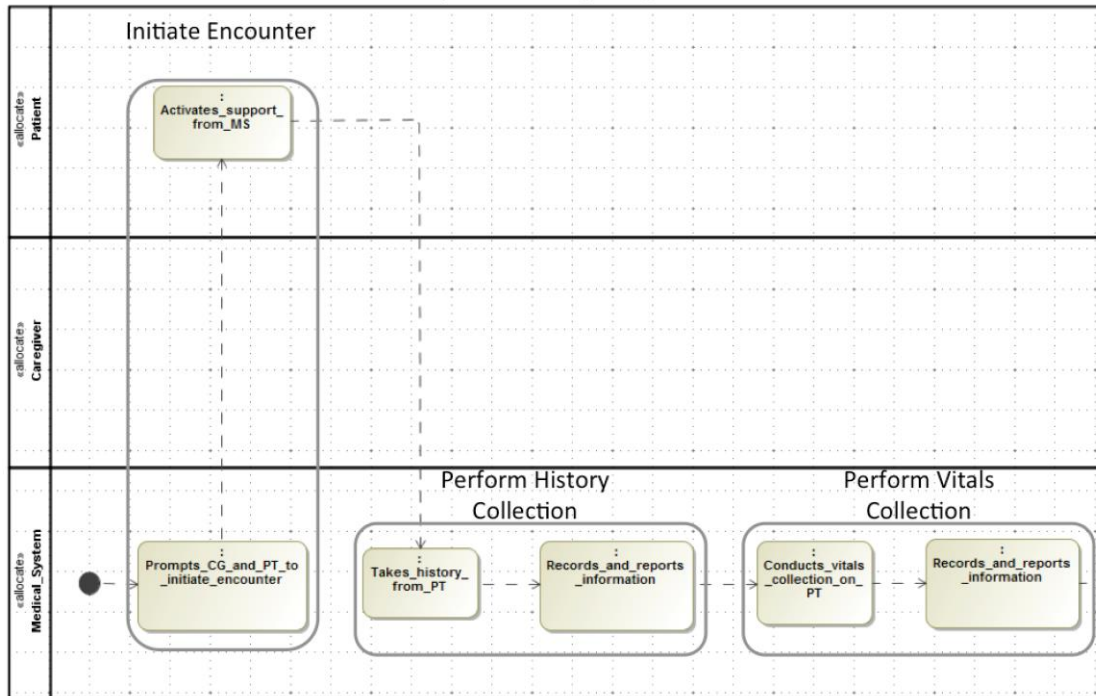

Figure 5. Portion of the dental exam scenario Activity Diagram.

B. Behavioral Interface Identification and Description

The ConOps scenarios are also captured as Sequence Diagrams in the SysML model. While the Activity Diagrams help to capture the flow of activities, Sequence Diagrams illuminate interactions among participants in the scenarios. Each ConOps scenario was deconstructed in Sequence Diagrams to identify interactions between the medical system, crewmembers (in patient or caregiver role), the exploration vehicle, and the ground system. This work helps to define functions the medical system must provide, flow of data and physical objects, and interfaces the medical system must provide to crewmembers and other systems. These products support functional decompositions for the medical system, crew, vehicle and ground systems, and the subsequent development of medical system and other system requirements.

Using the Dental Exam scenario as an example, Figure 6 highlights a few of the interactions that will occur between participants. The participants are shown as boxes at the top of the diagram, and interactions, or messages, are represented by the horizontal lines. The naming convention used in the messages abbreviates who the message is to (ms for Medical System in message 8), who the message content is from (Pt for Patient in message 8), and the type of information conveyed (VitalsInfo in message 8).

At the point in the scenario when message 8 occurs, the exam has been initiated, the patient has entered their updates to the history, and the medical system is collecting the vitals information directly from the patient. During the functional decomposition, this activity is abstracted from the diagram and from the perspective of the medical

system the action could be described as 'Obtains vitals info from patient'. Later in the model, this interface identification will turn into a requirement for a subsystem that is capable of obtaining vitals information directly from the patient. Message 9 shows that the medical system records and reports information. This message is unique in that it is not an interaction, but rather indicative of an autonomous activity the medical system should be able to perform. The physician then arrives and conducts the physical exam. Message 13 highlights the need for the medical system to accept inputs from the caregiver documenting the physical exam. The sequence diagram is a clear visualization of the interactions between actors in the system, and helps to identify additional functions and system interfaces that will receive futher detail in the requirements definition phase of the model design.
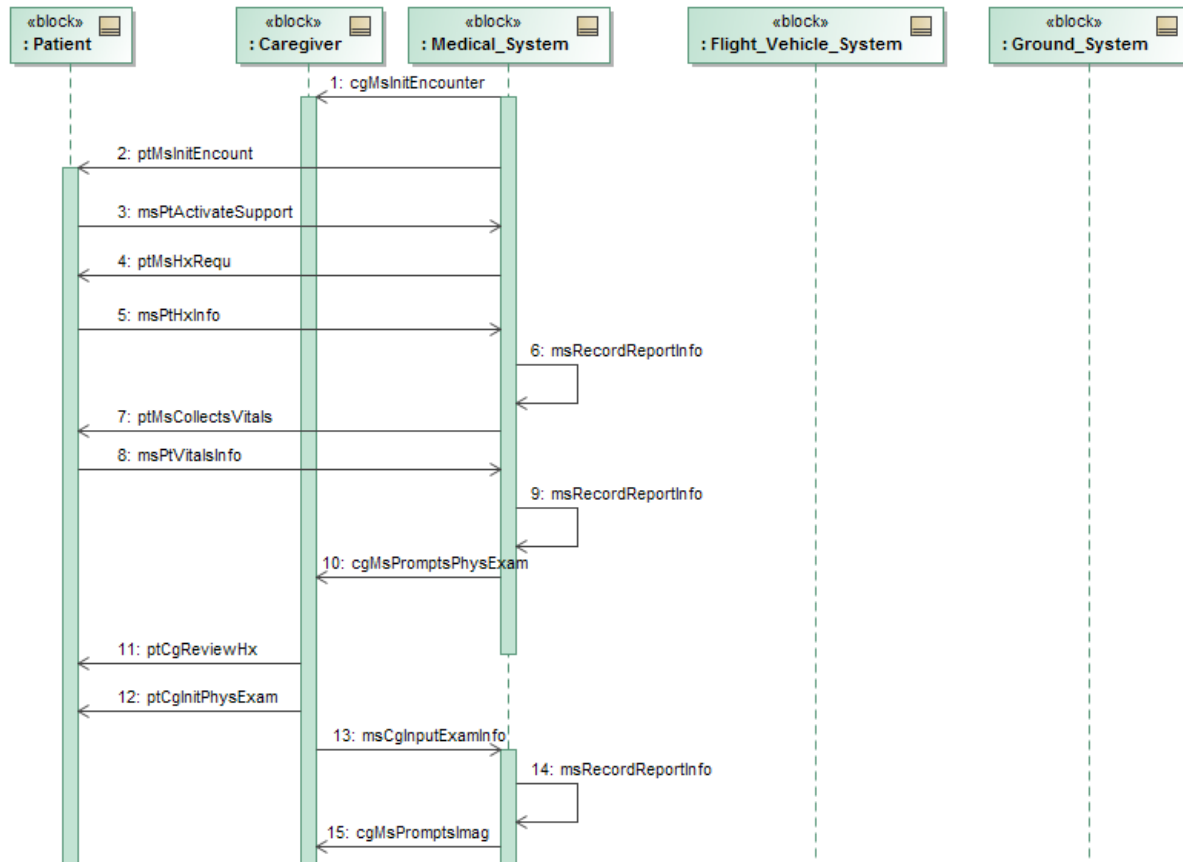

Figure 6. Portion of the dental exam scenario Sequence Diagram.

C. Functional Decomposition

The system behavioral content was analyzed and grouped into functions. A function typically starts with a verb and describes what the system does. These functions were further decomposed until each activity was mapped to a function. Information in this functional decomposition provides a more complete representation of the medical system "problem space". At the highest level, these functions aid in the development of the medial system architecture, which is the first foray into the "solution space".

Figure 7 shows how the medical system functions are broken into 8 sub-functions. One of these sub-functions is "Inform decisions on crew health actions".

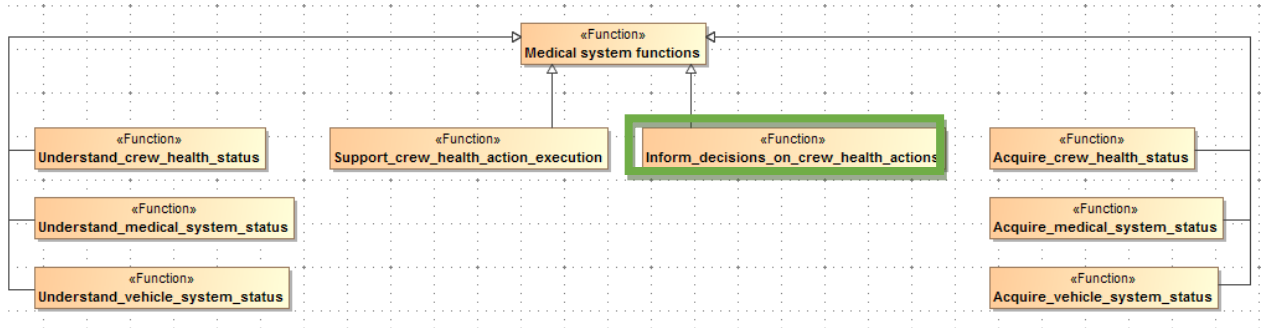American Institute of Aeronautics and Astronautics

Figure 7. High-level medical system functional decomposition.

Figure 8 further breaks-down this sub-function and shows the mapping of the activities to this sub-function. The earlier mentioned activity "Prompts CG and PT to initiate encounter" maps to the function "Prompt crew" which is a sub-function of "Inform decisions on crew health actions".
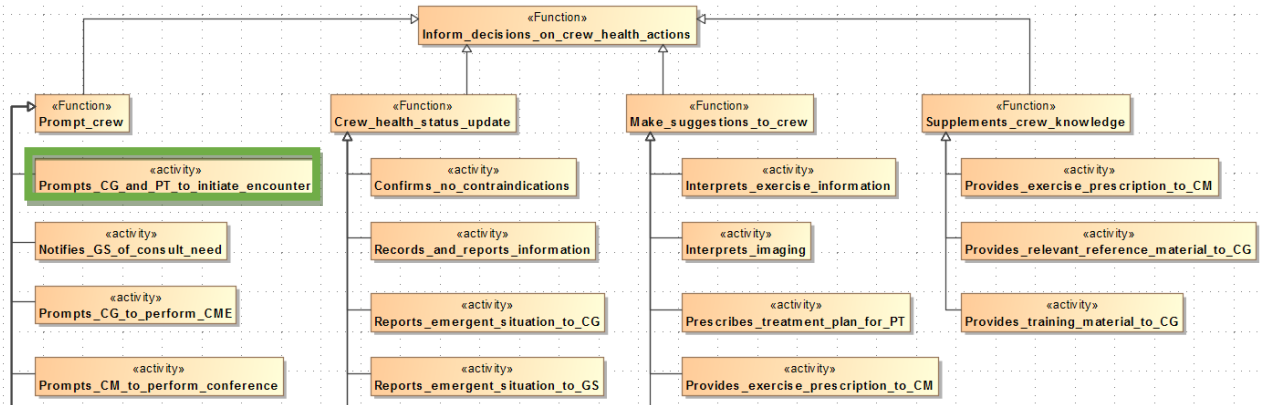

Figure 8. Sample scenario activities grouped under "Inform decisions on crew health actions".

V. Medical System Architecture Description

A draft system context and architecture was developed based on the needs, goals, and behaviors of the system. As requirements are written, the architecture will be refined, including defining lower levels of detail and eventually relating to physical components. Figure 9 presents a context architectural view centered on the Medical System as part of the overall vehicle Flight System. The focus of the initial ExMC MBSE activity is on the Medical System that will support crew for Deep Space Transportation missions (refer to Figure 1). The Flight System, Ground System, Caregiver, and Patient are included as high level components of this context view because the Medical System will have important interactions with each. For example, defining the required medical skillset of the Caregiver is important for understanding the necessary Medical System support.

Within the Flight System, traditional functional flight systems such as Structures and Avionics appear as the bottom row of blocks to provide context and awareness of future interfaces with those subsystems. For example, certain vehicle consumables, such as water and oxygen, will be required for medical purposes, but are not within the scope of the Medical System; they will likely be provided by the Environemental Control and Life Support System (ECLSS).
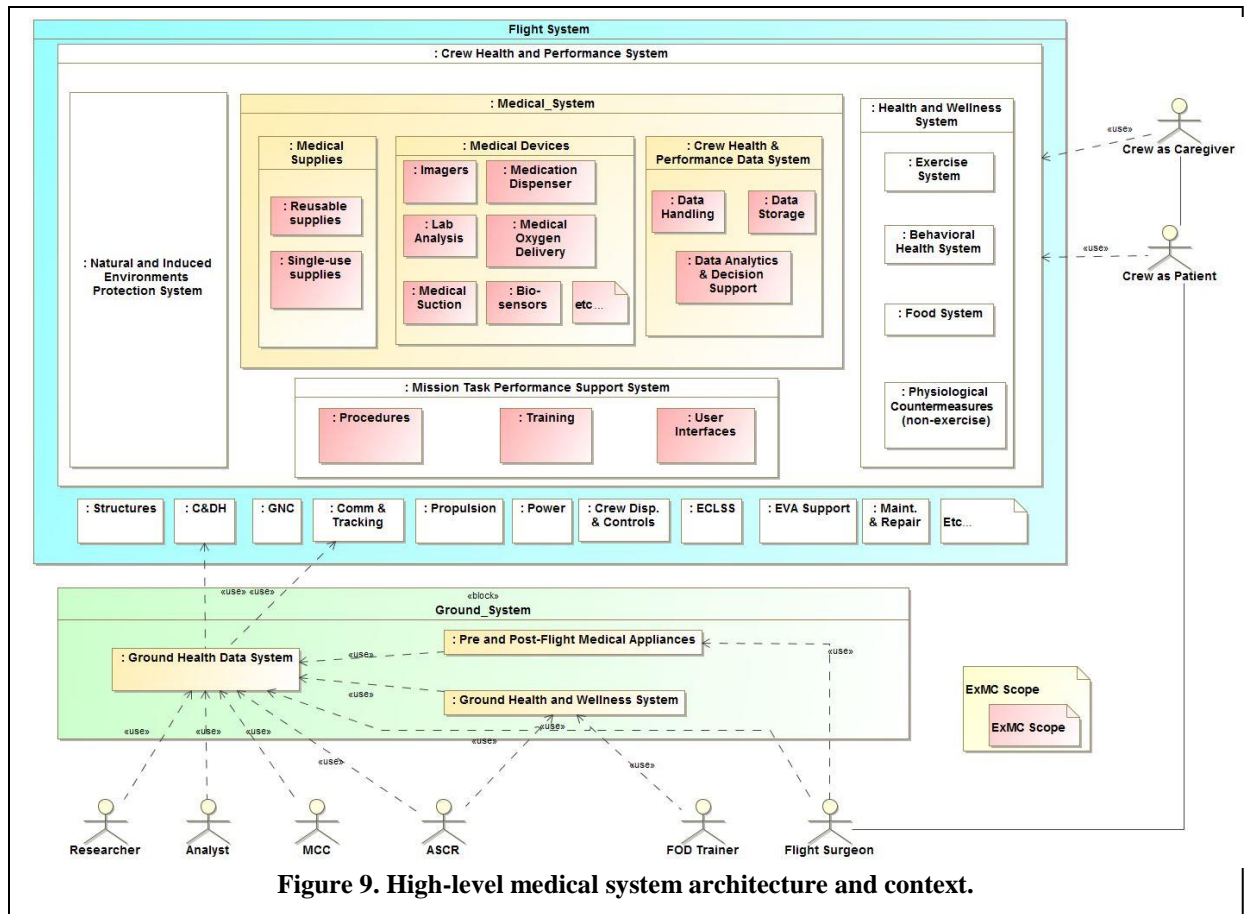
Figure 9. High-level medical system architecture and context.

Within the Crew Health and Performance (CHP) System, there are also blocks for the natural and induced flight environment protection not covered by other vehicle subsystems (e.g., radiation monitoring or protection not incorporated in the vehicle structure), and characterization of mission task support functions, which includes in-mission training for the crew and user interfaces for each device, including any device-specific procedure guidance, and user interfaces for the Crew Health & Performance Data System. A Health & Wellness System block is noted within the CHP System as it captures necessary crew support sytems such as the food supply, exercise system, and behavioral health support. Interfaces from devices in these categories to the CHP Data System are currently being identified. These devices are items that are likely referenced but not controlled by the Medical System architecture element.

The Medical System is characterized by three high level containing constructs:

Crew Health & Performance Data System

Within the scope of ExMC, the Crew Health & Performance Data System (CHPDS) is a core component of the overall Crew Health & Performance System (CHP). It is responsible for providing information and data to crew members via user interfaces. The data system is planned to collect all medically relevant information from disparate sources (environmental details, biosensors, exercise regimens, medications, lab diagnostics, and electronic medical records). These data are available for consultation onboard the spacecraft, and are also transmitted to the ground for additional analysis. Data privacy and confidentiality will be handled consistently with US laws and policies.

Besides data collection and storage, the data system provides data to other on-board systems as-needed through software interfaces. Another planned functionality of the system is to enable decision support capability by tracking and trending biometric details over time, and by implementing analytical algorithms that augment the knowledge of the decision-making crewmember. This is important for deep space missions where operations demand crew autonomy. The system is anticipated to afford such analytic capabilities by combining information on the crew and the vehicle's environment. Some examples of the information that may be analyzed include medical image interpretation, biomedical metrics identification, medical history notification, exercise performance review and vehicle environment data review.

Medical Devices

This block categorizes devices that may be implemented to perform medical tasks or procedures. These devices are defined by their interface(s) with one or more other systems in the form of power, data (physiological and laboratory), vacuum, or consumables. Devices that exist in this category may include biosensors, which collect and transmit physiological data, and pharmaceutical hardware, which aid in the dispensing of medication. Note that in the early stage design process and within the context of model-based system development this will typically be a large list of items where, for a given system architecture option, a subset of items is selected for incorporation into the habitat design. This "instancing" of items for the purpose of characterizing a particular design provides a means to characterize and formally track design trades.

Medical Supplies

This block categorizes items used for medical care that are consumable, do not require power, or do not generate data. These items also lack interfaces to other systems for vacuum or consumables. For example, this block includes reusable items, such as scissors, splints, and sharps containers, and single-use items, such as masks, hand sanitizer, gloves, waterproof tape, catheters, instant ice, bandages, needles, and gauze. These items are tracked here to define an understanding of the quantities required.

VI. Initial Traceability Development

The ability to see relations between model elements is an important feature enabled by a strongly architected model-based approach. Example SysML relationships are "allocate", "derive", "verify", and "satisfy". Figure 10 shows the allocation of two activities (orange) to the blocks (brown), or elements of the system, responsible for performing that activity. The use of an activities allocation matrix (Figure 10) is an excellent means of observing the often large number of allocations and interrelationships. In this figure, a subset of activities (rows) and blocks (columns) are shown. The intersections of activities and blocks populated with an upward right arrow indicates an allocation of the activity to the block.
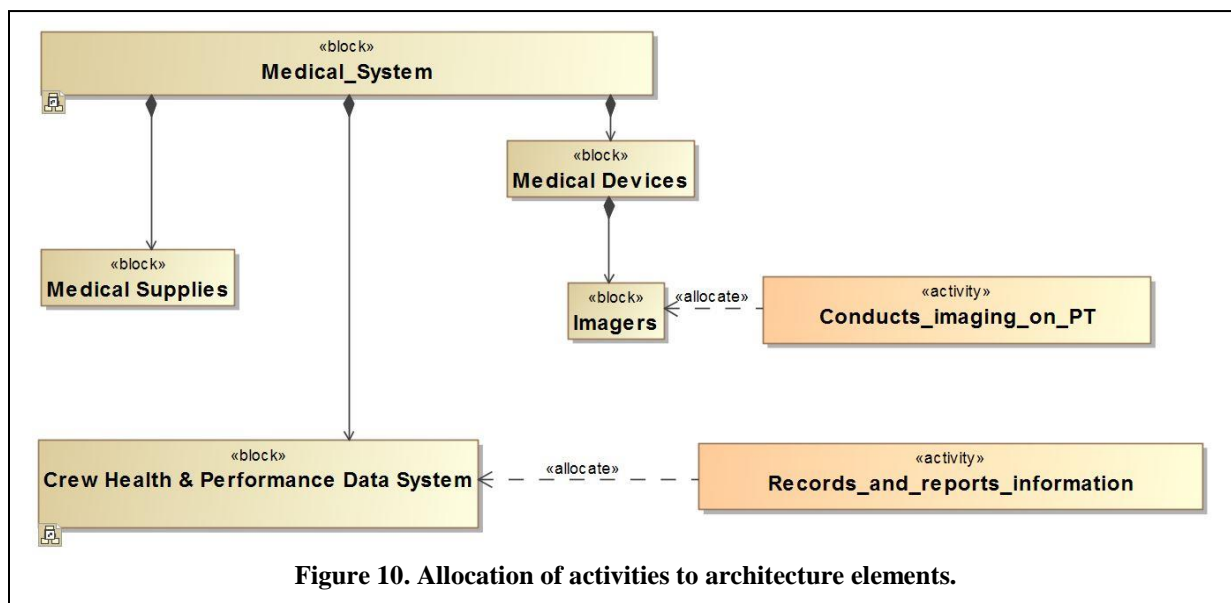

Figure 10. Allocation of activities to architecture elements.

Figure 11. Traceability matrix for allocated activities.

Blocks with appropriate behaviors are the model elements that satisfy program requirements. Requirement satisfaction will be tracked via a requirements allocation matrix, similar to the activity allocation matrix in Figure 11. The "satisfy" relationship, analogous to the "allocate" relationship, enables the traceability. Establishing the ability for requirements and subsequent solution options to be traced to content in key documents, such as NASA-Standard 3001 [7] and the ConOps, will also lead to the identification of technology development needs. Relationships of requirements to rationales and reference information will also be tracked in the ExMC SysML model.

VII.   Verification and Validation Approach

The ExMC approach for verification and validation plans is to take advantage of terrestrial analogs and near-Earth exploration system maturation. A series of stepping-stone medical system developments aboard ISS, cis-lunar missions, and flights beyond cis-lunar space will be utilized for maturation of medical system products. These developments will provide an opportunity to interface with vehicle design groups, especially those also utilizing the MBSE approach, and further streamline processes across NASA mission development teams. Development of the medical system concepts of operations, and future SE products such as requirements and trade study tools, are being developed to coordinate with emerging exploration class vehicles and habitats.

VIII.   Future Work

The ExMC SE team will continuing iterating with stakeholders on needs, goals, and high-level behaviors, and progress to define system measures of effectiveness and performance. The team will continue the analysis of behavioral content to define requirements and iterate on architecture. The suite of tools to support exploration system trade study analyses will be architected and development of those tools will be undertaken. The team expects increasing integration efforts with those undertaking work on other areas of the Crew Health and Performance System, and the broader exploration habitat and mission development.

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IX. Conclusion

A strong systems engineering foundation to support medical system definition and analyses that will inform research activity needs and prioritization has been established. Key stakeholders have been identified and engaged to understand their needs. Medical system behavioral content has been created to inform initial architecture development. A Model-Based Systems Engineering approach has been put in place to enable effective communication and coordination with exploration system maturation.

Acknowledgments

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